Dynamics of a laser-assisted Z-pinch EUV source

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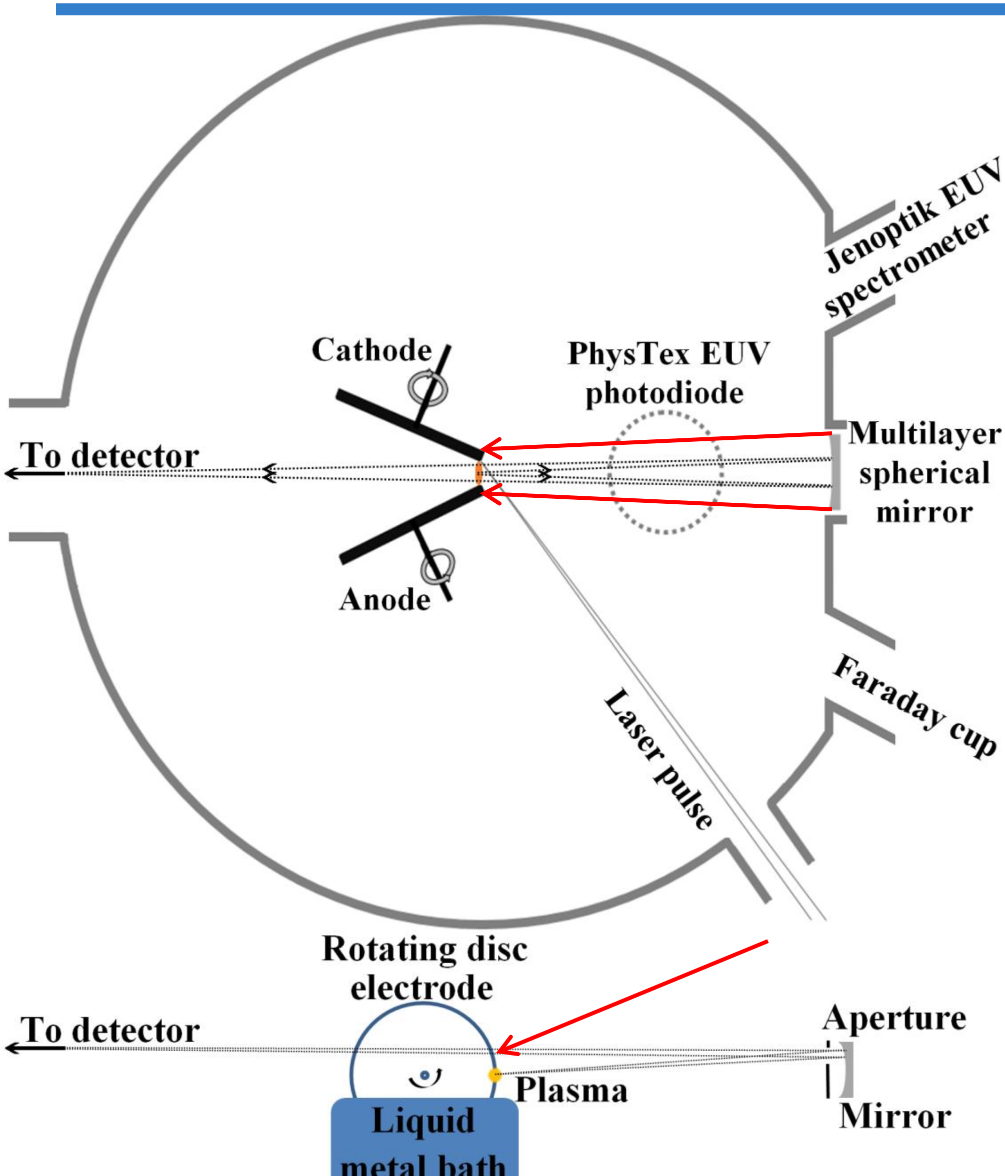
EUV Litho Source Workshop – 6th November 2013

Laser Assisted Vacuum Arc (LAVA) lamp



Diagnostic techniques:

- absolutely calibrated time integrated EUV spectroscopy
- 2 μm spatially resolved time integrated in-band EUV imaging
- in-band EUV filtered absolutely calibrated photodiode
- EUV filtered fast photodiode
- **time- and spatially-resolved fast gated visible emission spectroscopy**
- **time of flight of ions with Faraday cup**
- Rogowski coil characterisation of discharge current
- Angular thin film deposition debris study

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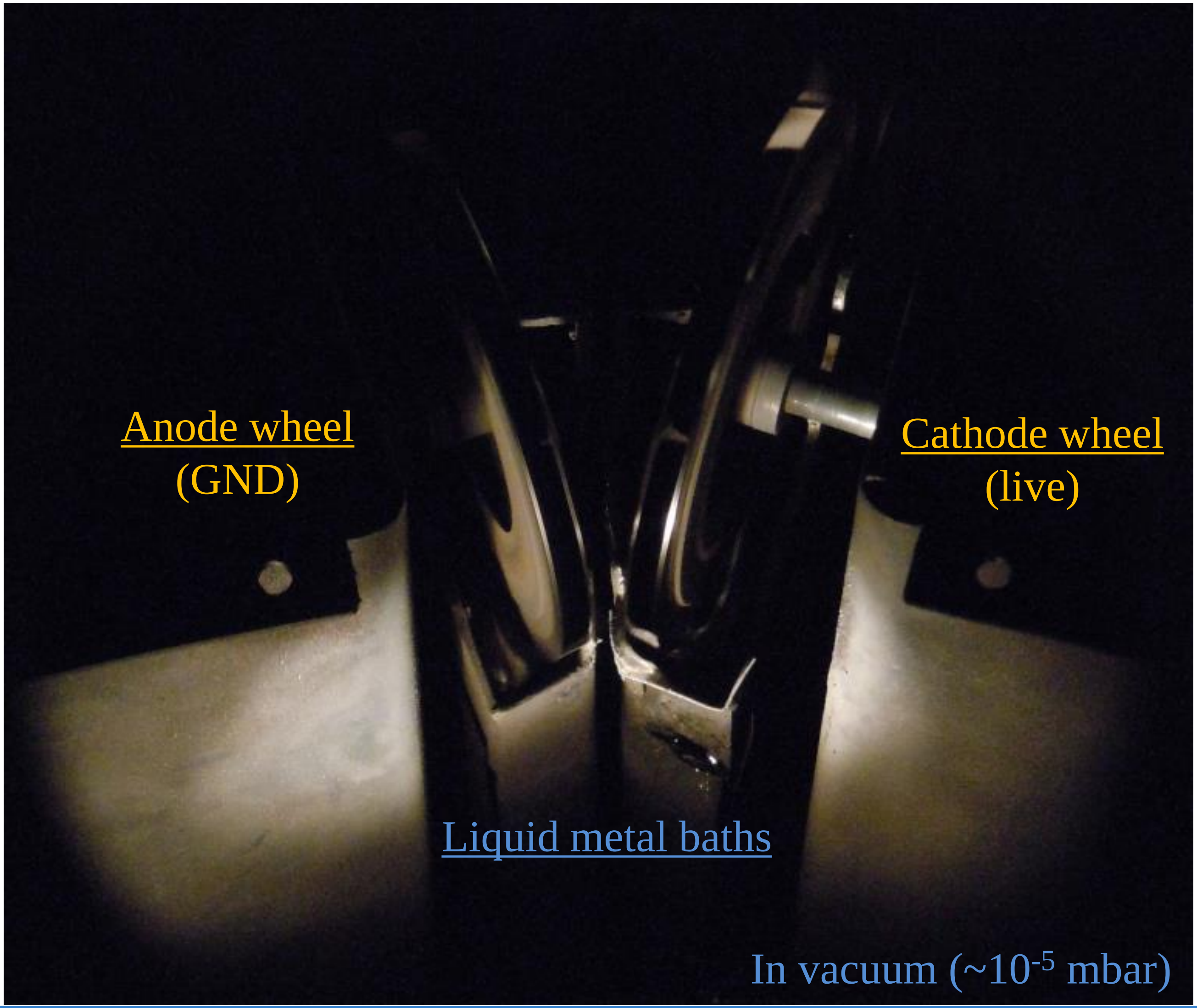
Laser Assisted Vacuum Arc (LAVA) lamp

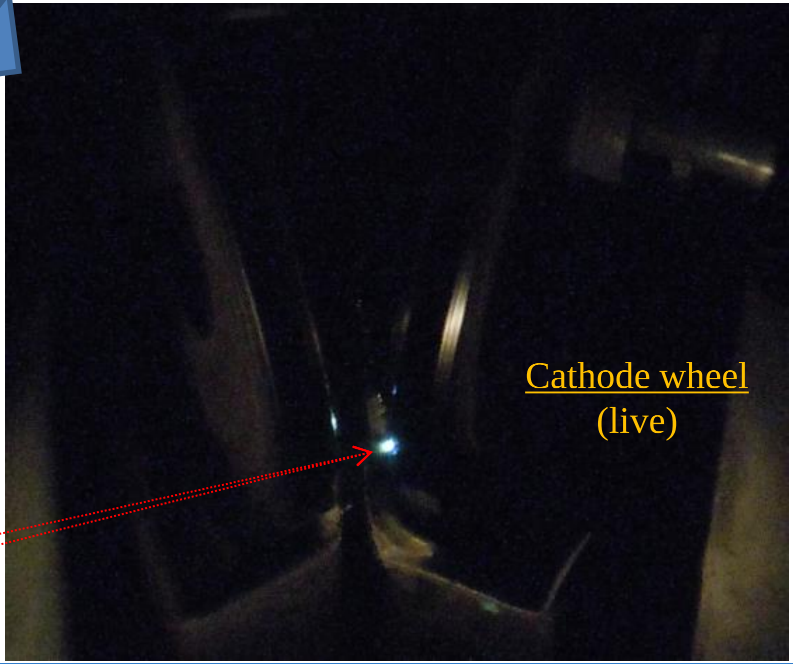
Two rotating disc electrodes with a thin liquid metal coating,



Laser Assisted Vacuum Arc (LAVA) lamp

Two rotating disc electrodes with a thin liquid metal coating,

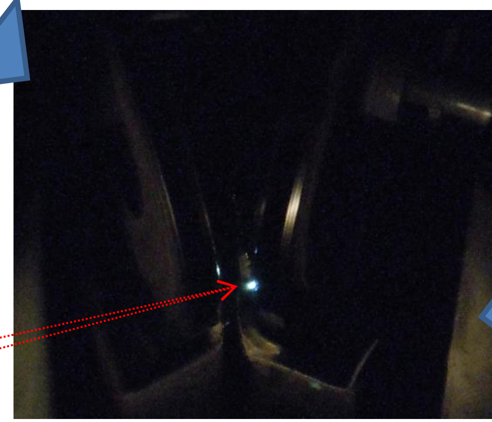
ablate the cathode,



Laser Assisted Vacuum Arc (LAVA) lamp

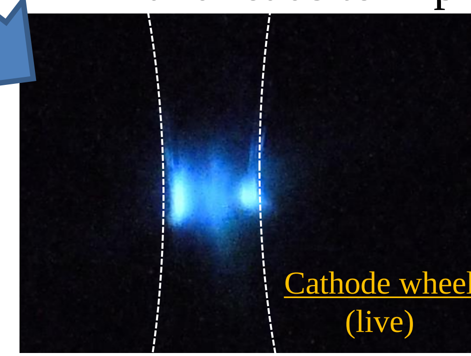
Two rotating disc electrodes with a thin liquid metal coating,

ablate the cathode,



Laser pulse

laser plasma triggers discharge
and leads to Z-pinch.



- Work just published:
  I. Tobin, L. Juschkin et al., Appl. Phys. Lett. **102**, 203504 (2013)

Laser Assisted Vacuum Arc (LAVA)

Two rotating disc el

side),

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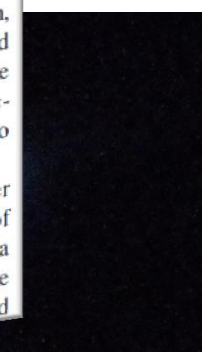

Appl. Phys. Lett. **102**, 203504 (2013)

Laser triggered Z-pinch broadband extreme ultraviolet source for metrology

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We compare the extreme ultraviolet emission characteristics of tin and galinstan (atomic %: Ga: 78.35, In: 14.93, Sn: 6.72) between 10 nm and 18 nm in a laser-triggered discharge between liquid metal-coated electrodes. Over this wavelength range, the energy conversion efficiency for galinstan is approximately half that of tin, but the spectrum is less strongly peaked in the 13–15 nm region. The extreme ultraviolet source dimensions were 110 ± 25 μm diameter and 500 ± 125 μm length. The flatter spectrum, and −19 °C melting point, makes this galinstan discharge a relatively simple high radiance extreme ultraviolet light source for metrology and scientific applications. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4807172]

Laser produced plasmas (LPPs) and discharge produced plasmas (DPPs) have been extensively studied as radiation sources for extreme ultraviolet (EUV) lithography at 13.5 nm.[1] Current state-of-the-art sources use tin as the emitter material because it has strong emission at 13.5 nm due to 4 p–4 d and 4 d–4f unresolved transition arrays (UTAs) in Sn XI–XIV.[2] Discharge sources have the potential to provide higher wall-plug efficiency than LPPs.[3] EUV emission from a Z-pinch in a laser-triggered discharge between rotating electrodes coated with liquid tin has been studied previously.[4,5] The liquid metal coating overcomes the problem of electrode erosion, but it is necessary to maintain the tin above its melting temperature of 232 °C. The EUV emission spectrum of pure tin plasma, at the appropriate conditions, is relatively narrow-band, with ~50% of emission in the 13–15 nm range. For EUV metrology, the source parameters of interest are spectral radiance, wavelength range, and emission uniformity, as well as cost and ease of operation. Compared to pure tin, galinstan (at. %: Ga: 78.35, In: 14.93, Sn: 6.72) has spectrally flat broadband emission in the laser triggered discharges in tin which are similar to the state-of-the-art sources for 13.5 nm lithography.

The Z-pinch EUV source is based on a laser-triggered discharge struck between two rotating disc electrodes, which are coated in liquid metal by partial immersion in liquid metal baths. The source was developed at the Russian Institute of Spectroscopy (ISAN).[5] Figure 1 shows plan and side views of the electrode geometry and the arrangement of the diagnostic instruments. The disc electrodes are tilted so that the separation at closest approach is 4 mm. For galinstan, the metal baths are not heated, while for tin they are heated to 300 °C. The anode is grounded to the chamber while the cathode is connected to the live electrode of a 0.39 μF capacitor bank. The charging voltage was varied from 2.5 to 5.5 kV (1.25 to 6.05 J).

The discharge is triggered using a 1064 nm, 30 ns laser pulse to form a LPP on the cathode electrode at the point of closest approach to the anode. The laser is focused to a 400 μm diameter spot and the energy was varied in the range of 5–80 mJ by means of a rotatable half-wave plate and

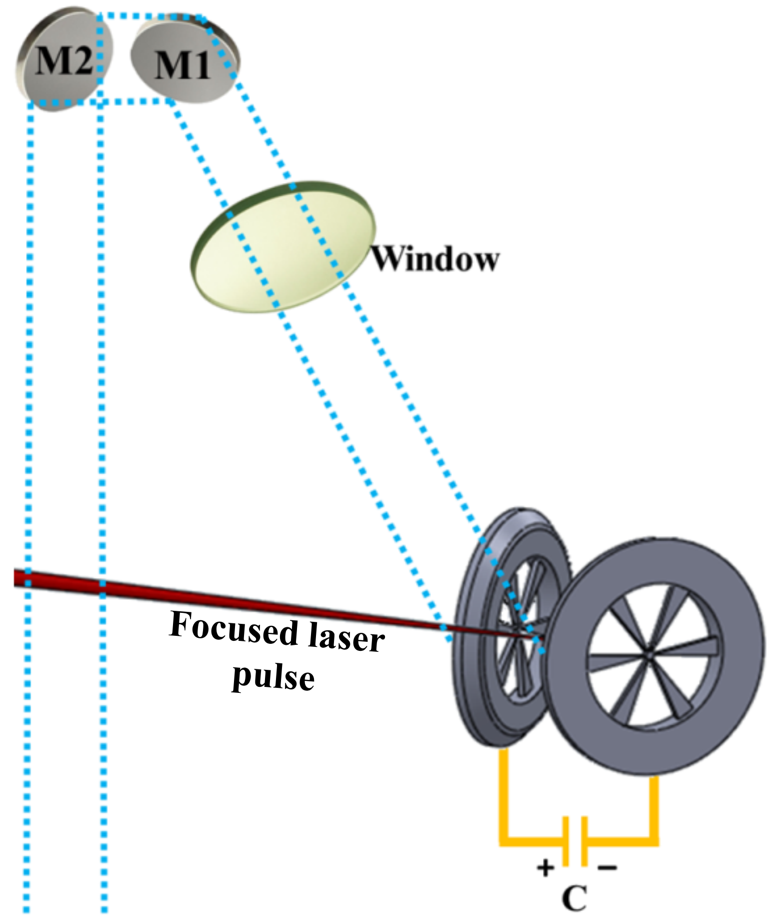
- Work just published:
  I. Tobin, L. Jus

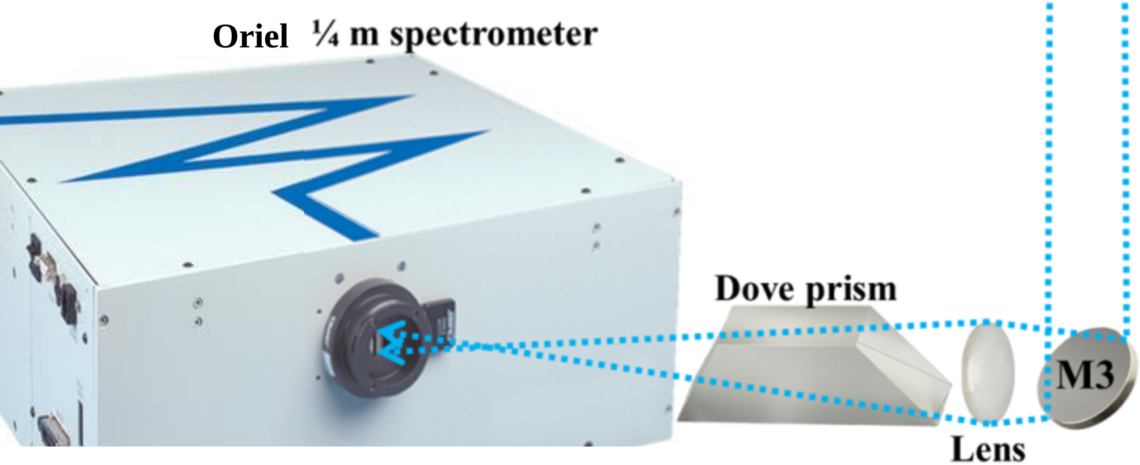
Laser Assisted Vacuum Arc (LAVA) lamp

- **Visible spectroscopy:**

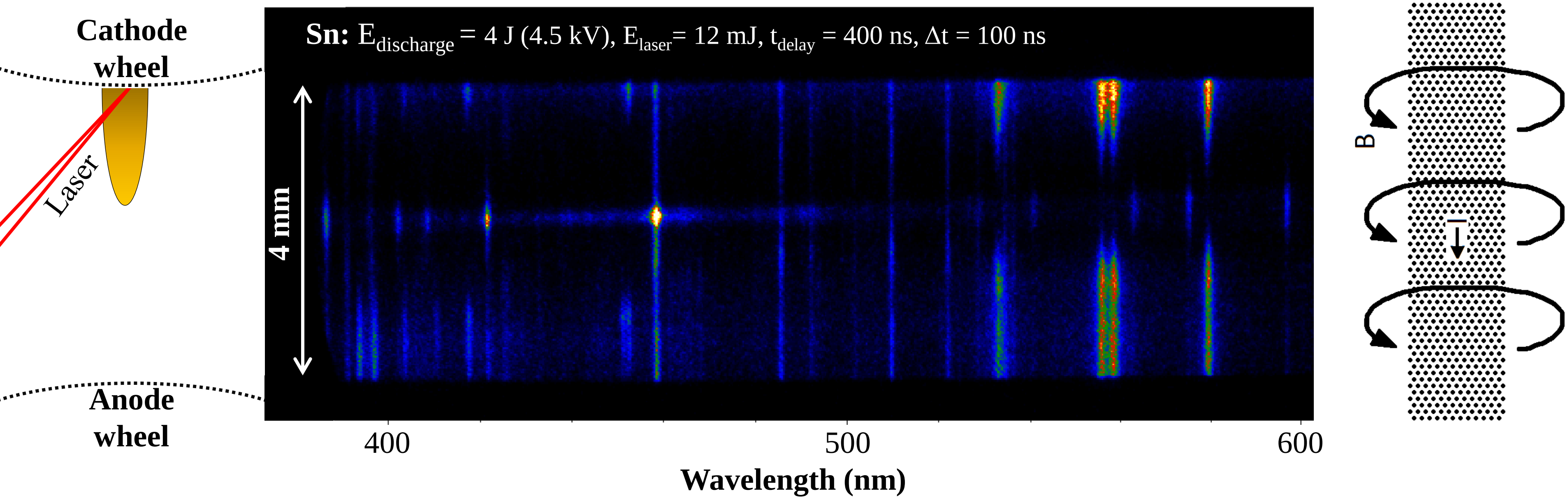
  - **4 mm** inter electrode gap imaged onto **3 mm slit** of Czerny-Turner spectrometer via 3 silvered mirrors and a Dove prism

  - Spectral range of ~ **380 nm – 610 nm**





Laser Assisted Vacuum Arc (LAVA) lamp



- Spatial resolution of **~ 300 µm** (4 mm imaged to 4.8 mm at ICCD with 26 μm^2 pixel size)
- Temporal resolution **~ 8 ns** (minimum ICCD gate time **Δt**)
- Spectral resolution **~ 1 nm** (instrumental broadening)

➢ Spectra recorded for t_{delay} = **0 – 1.4 µs**, $V_{discharge}$= **3 kV – 6 kV**, with **pure Sn** and **galinstan**

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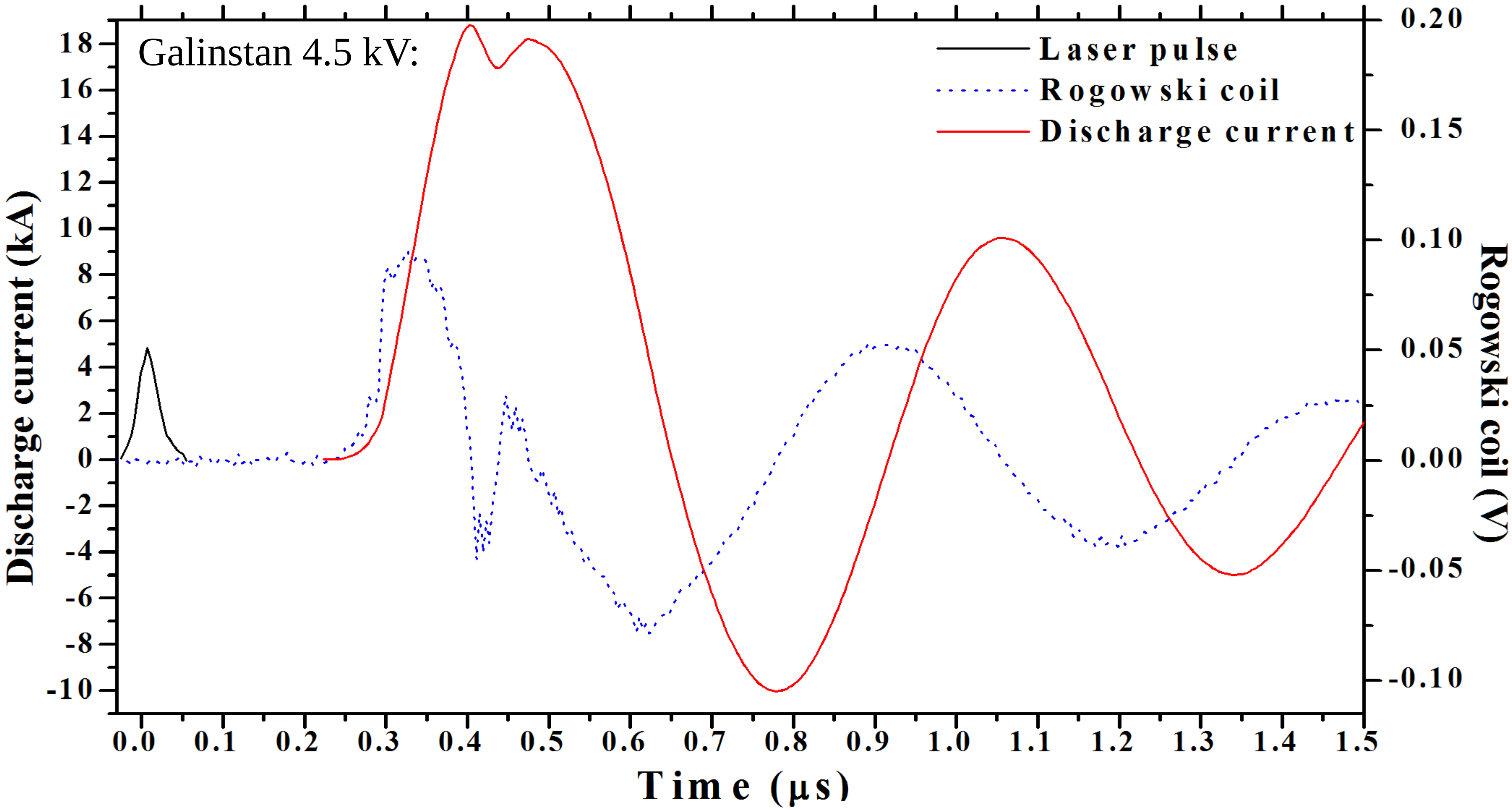
Laser Assisted Vacuum Arc (LAVA) lamp

Time delay between **laser pulse & onset of discharge** varied for material:

galinstan: **~ 300 ns** **τ ~ 620 ns**

pure tin: **~ 200 ns** **τ ~ 600 ns**



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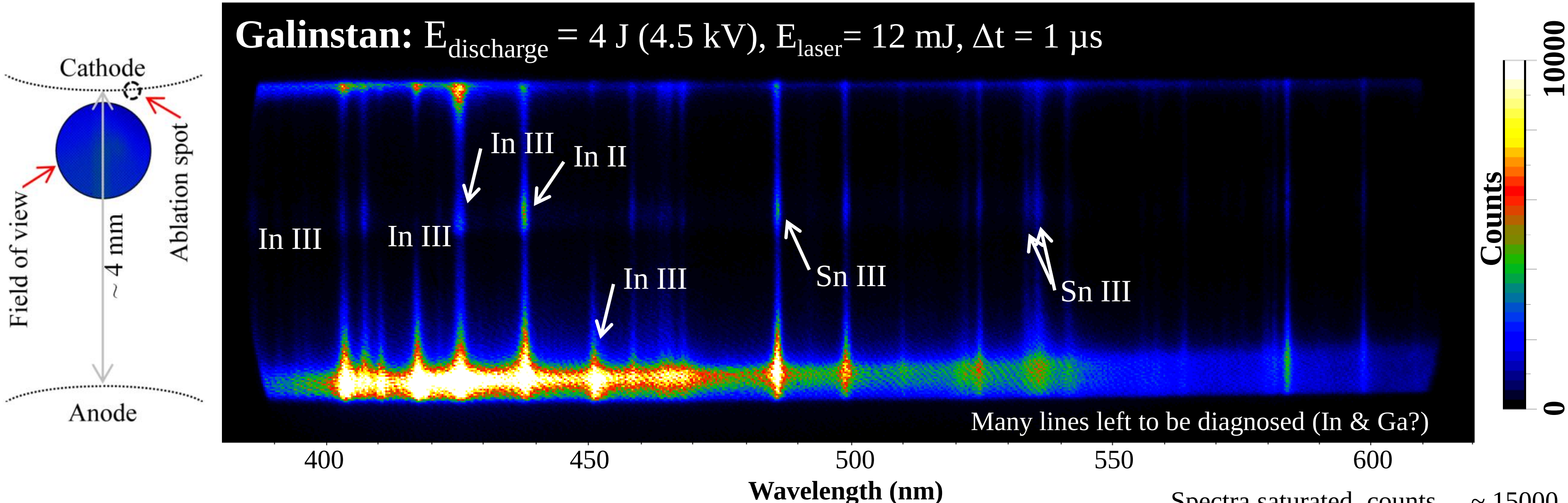
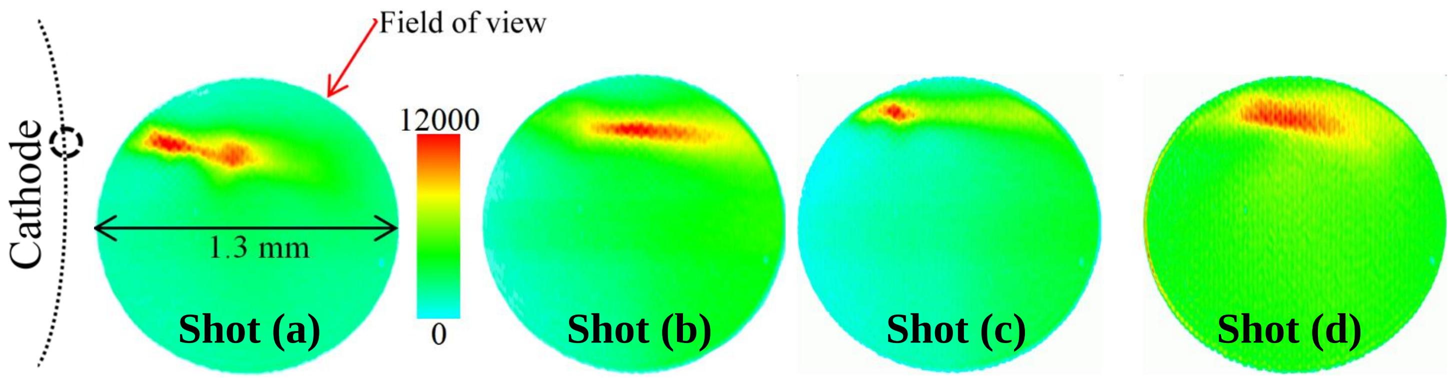
Laser Assisted Vacuum Arc (LAVA) lamp



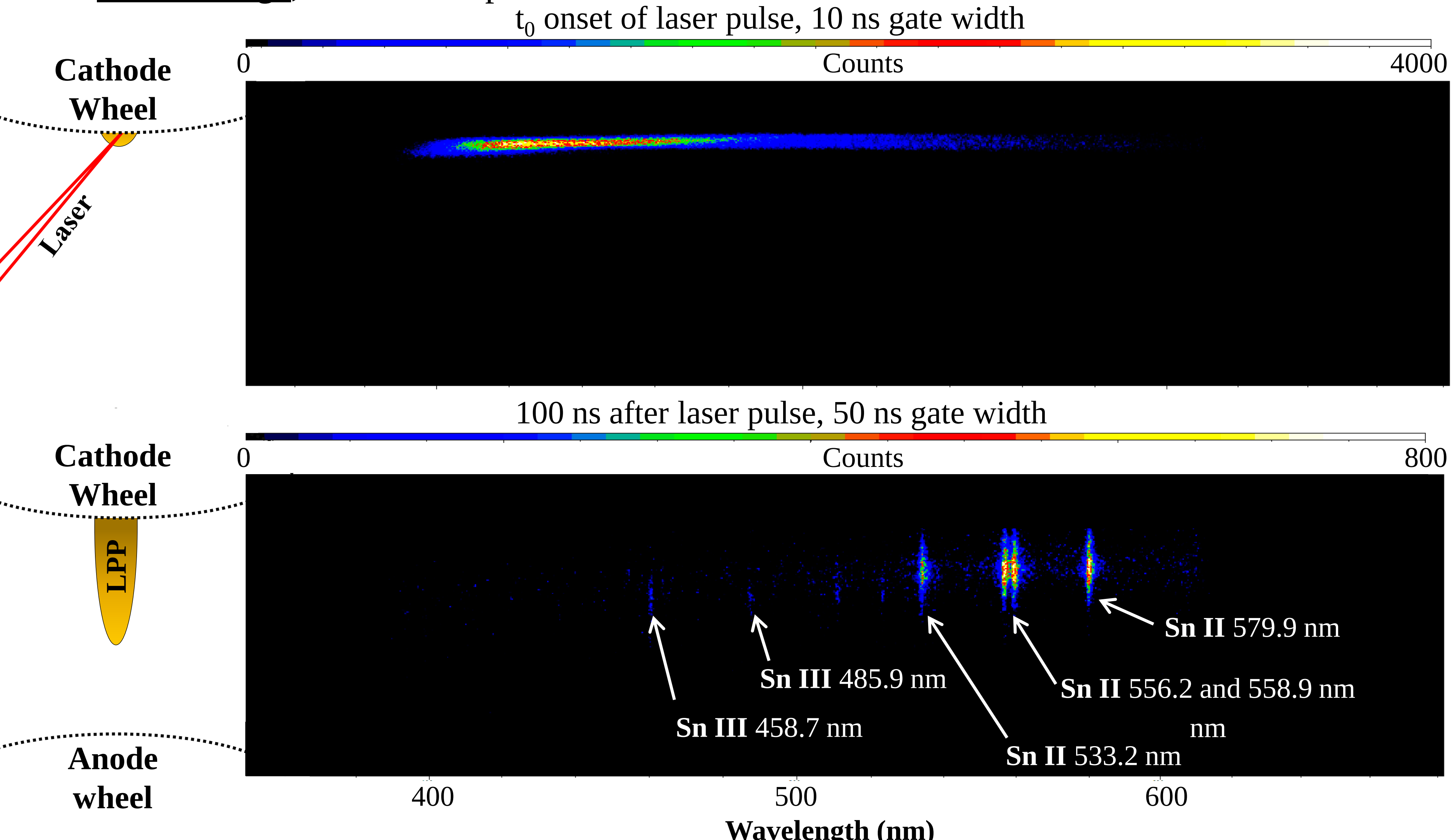
Spectra saturated, $counts_{max}$ ~ 15000

EUV emitting region (6 nm – 18 nm) time integrated imaging:

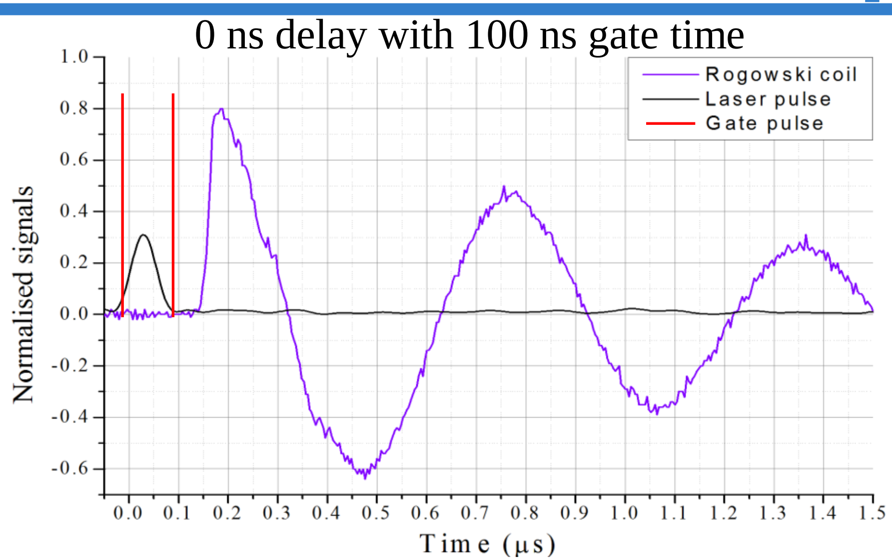


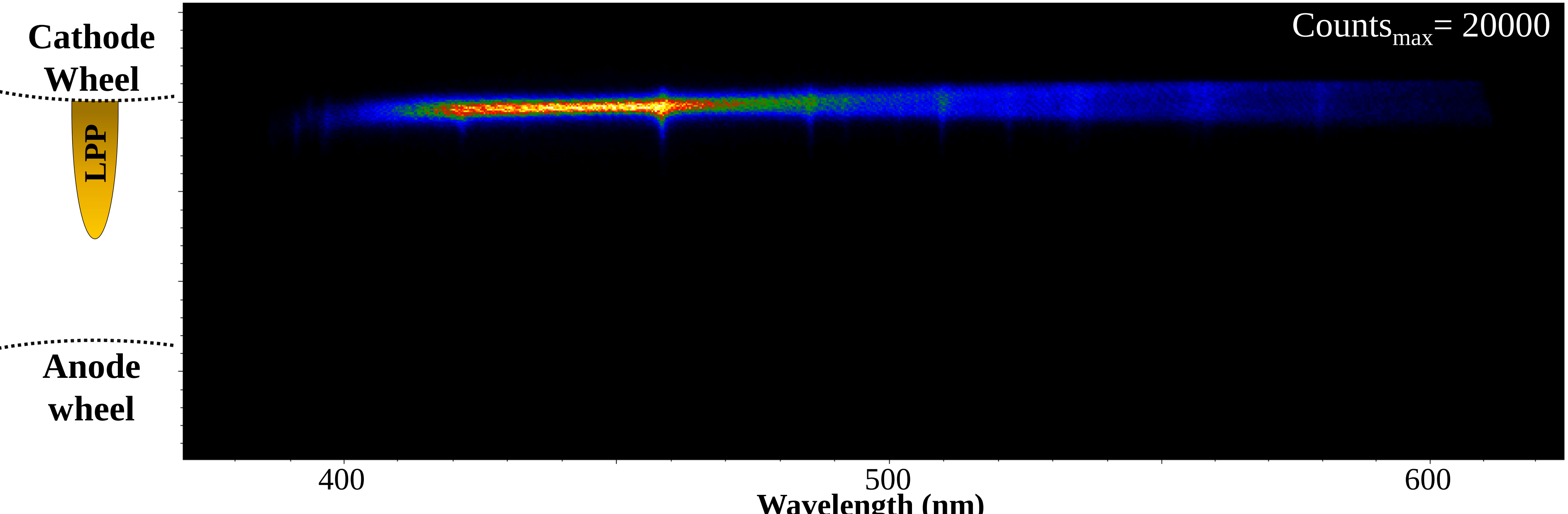
Laser Assisted Vacuum Arc (LAVA) lamp

- No discharge, 12 mJ laser pulse on Sn:



Laser Assisted Vacuum Arc (LAVA) lamp





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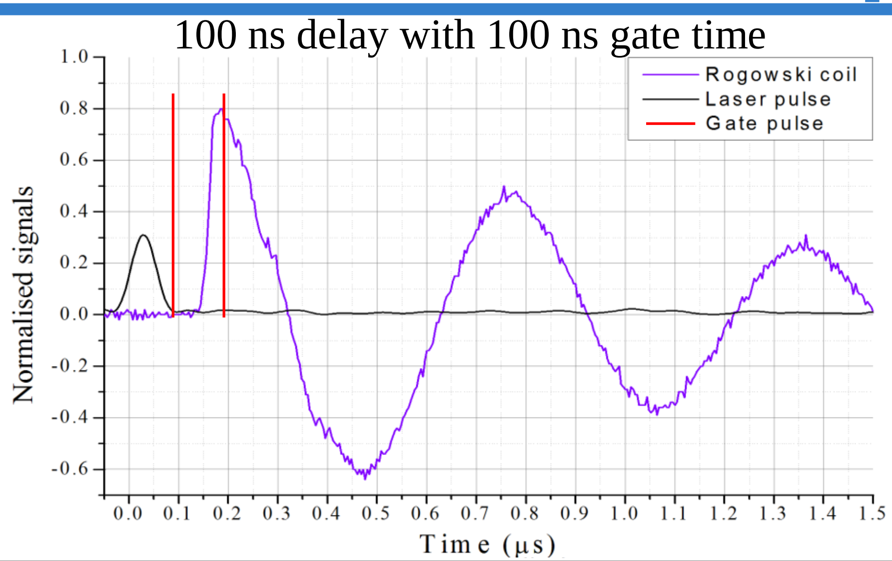

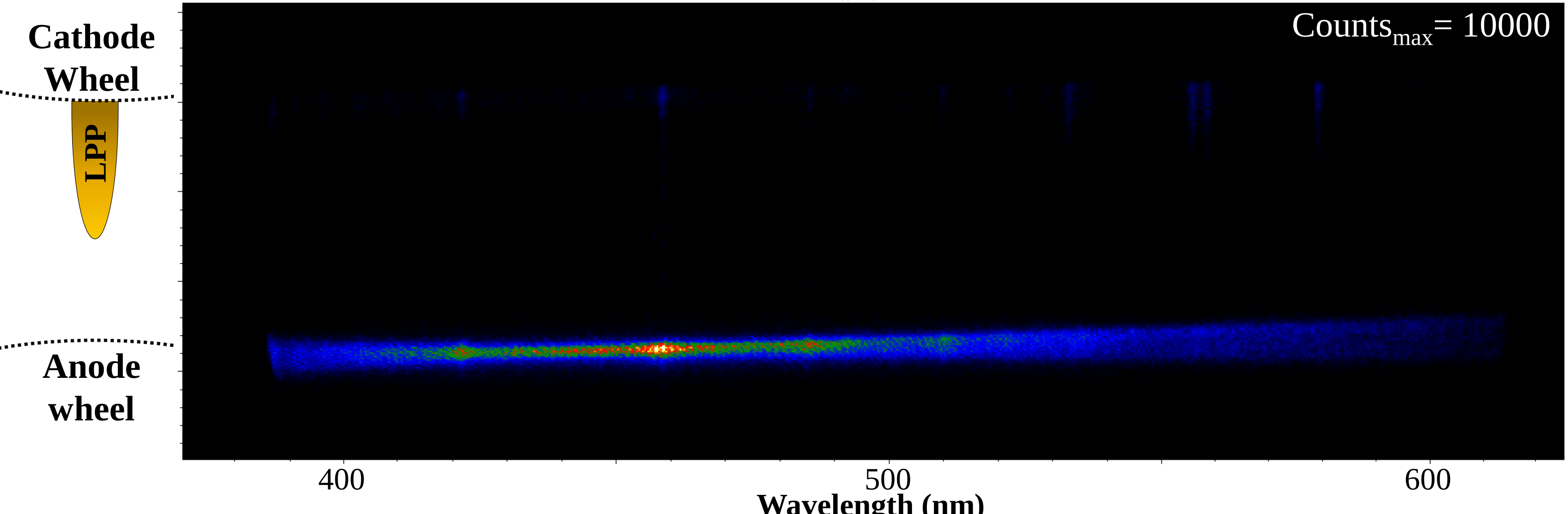

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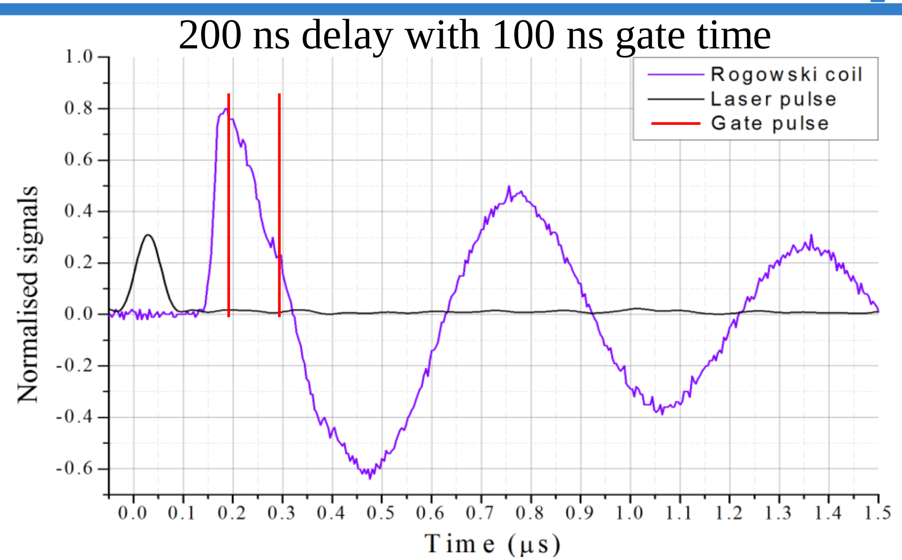
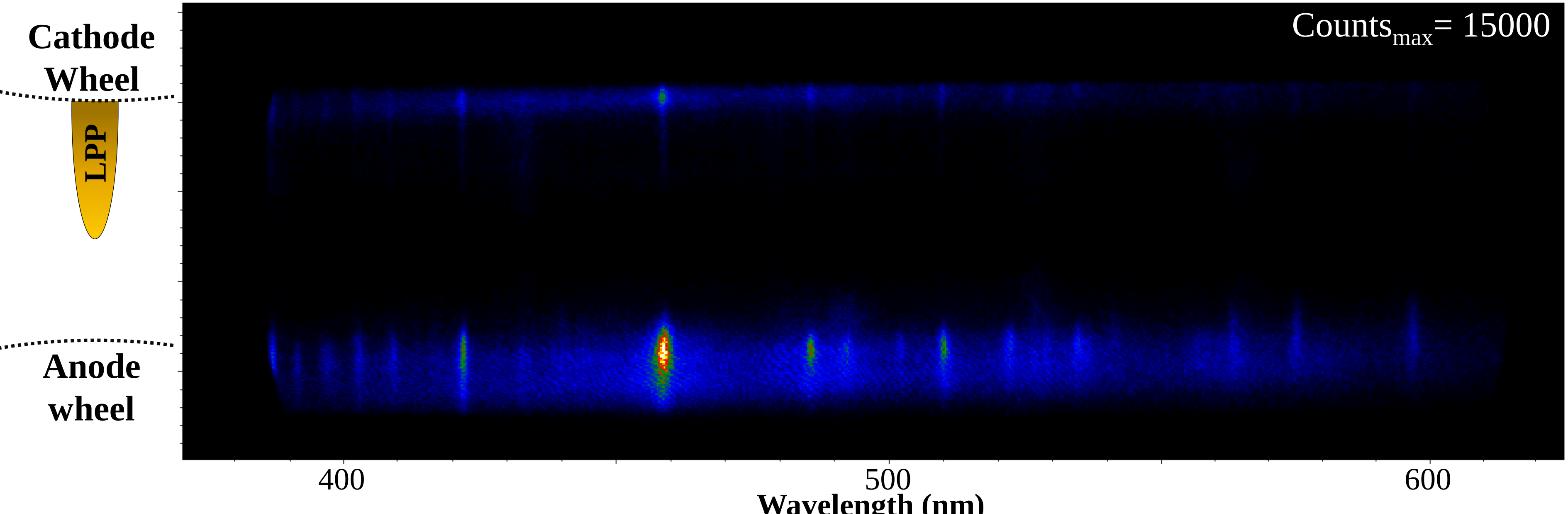
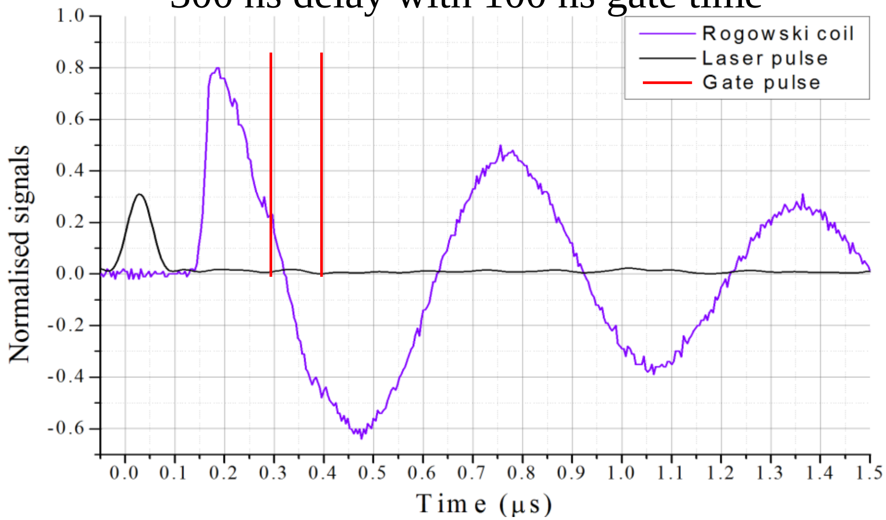
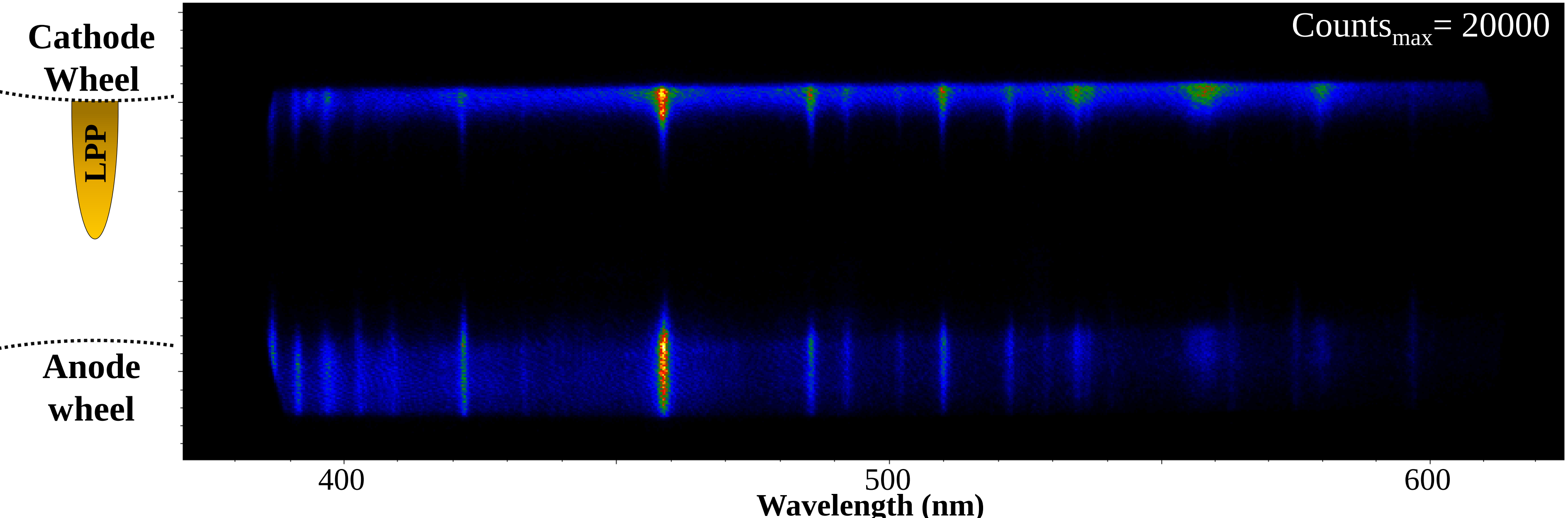




Laser Assisted Vacuum Arc (LAVA) lamp

300 ns delay with 100 ns gate time





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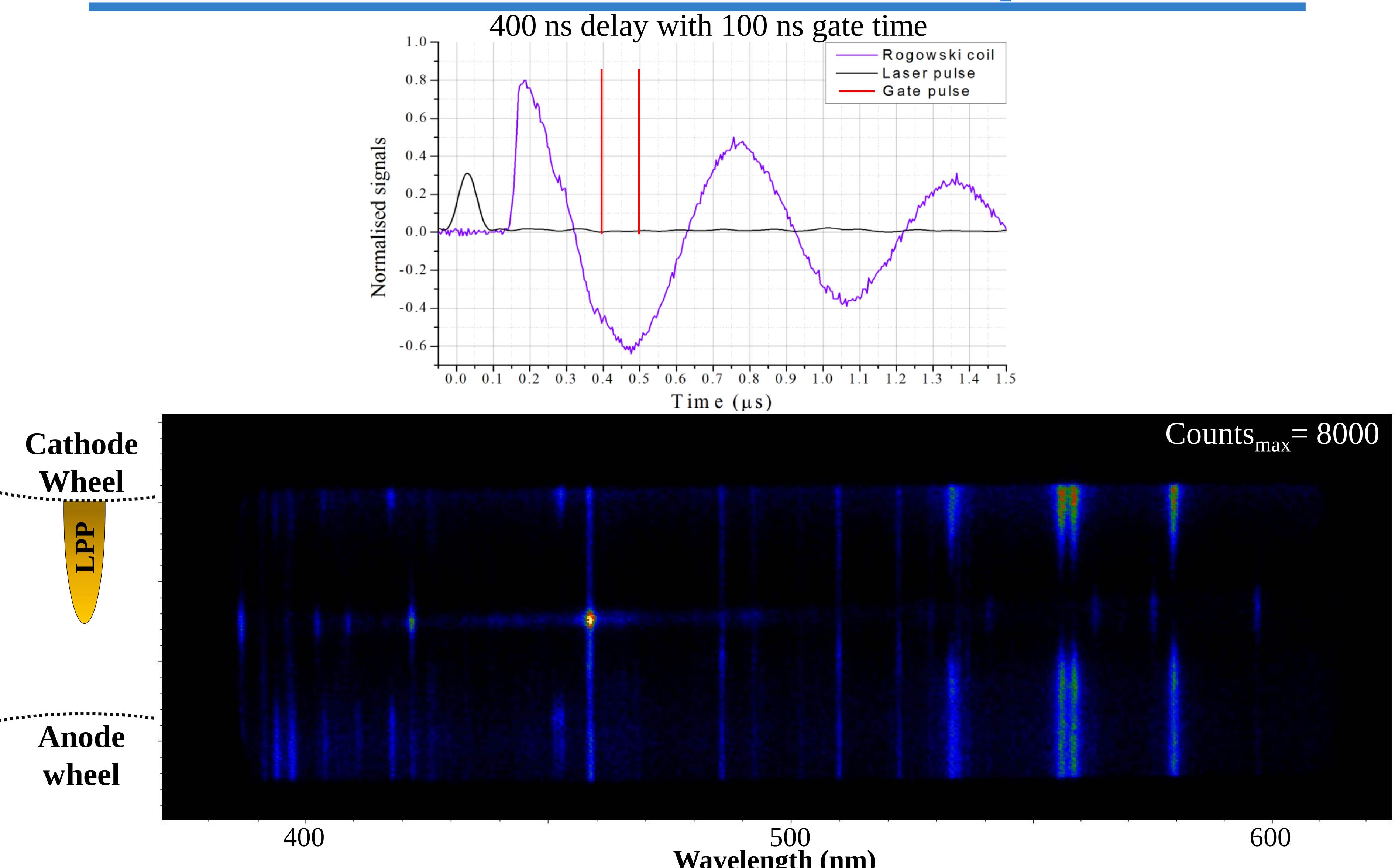
Laser Assisted Vacuum Arc (LAVA) lamp



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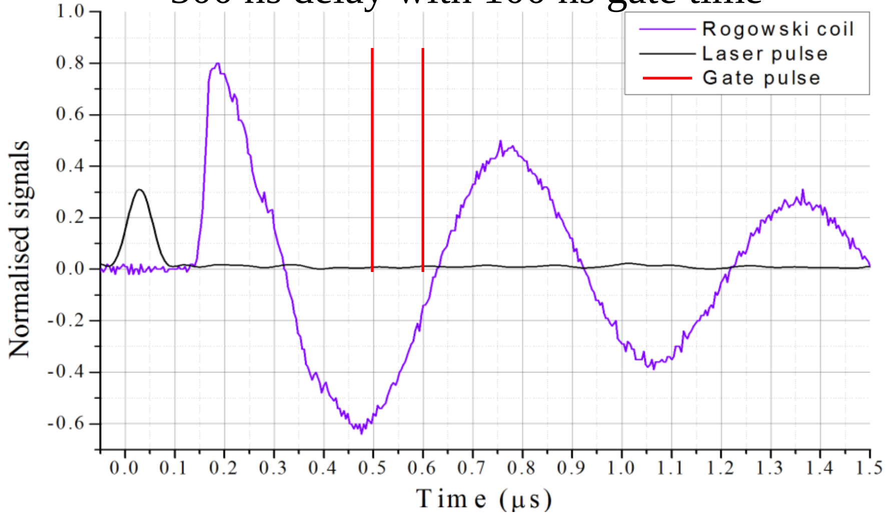
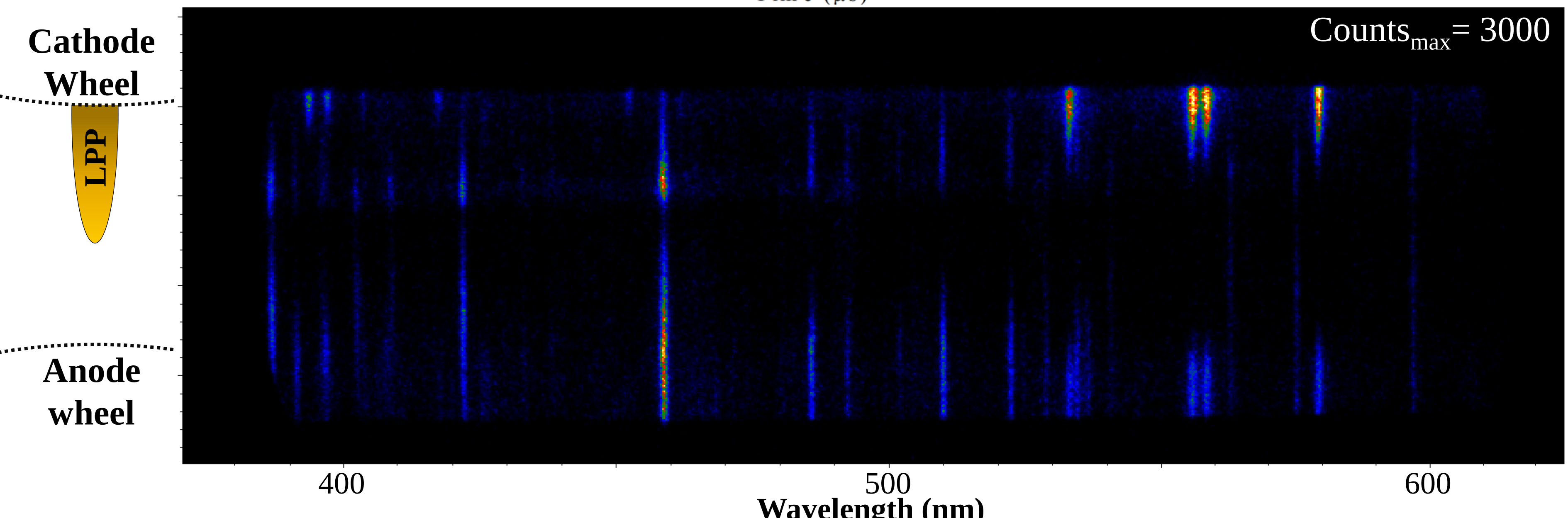
Laser Assisted Vacuum Arc (LAVA) lamp

500 ns delay with 100 ns gate time





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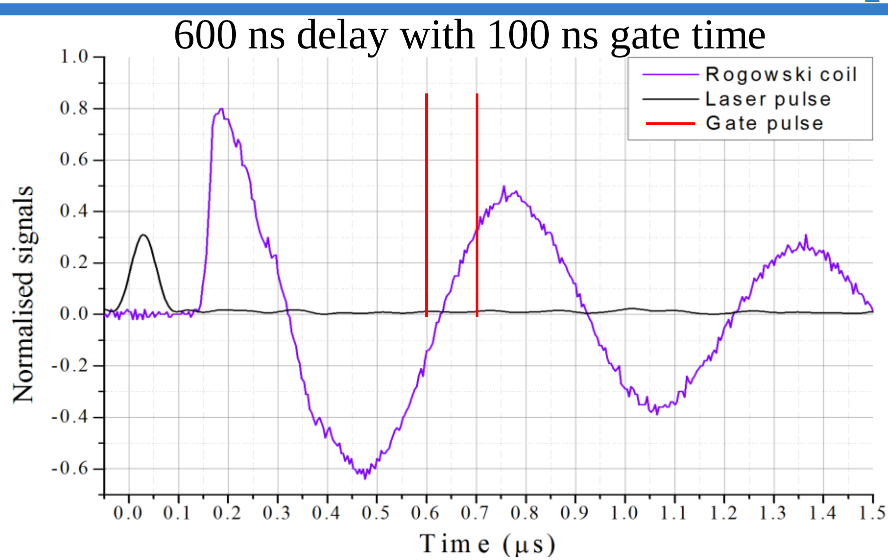

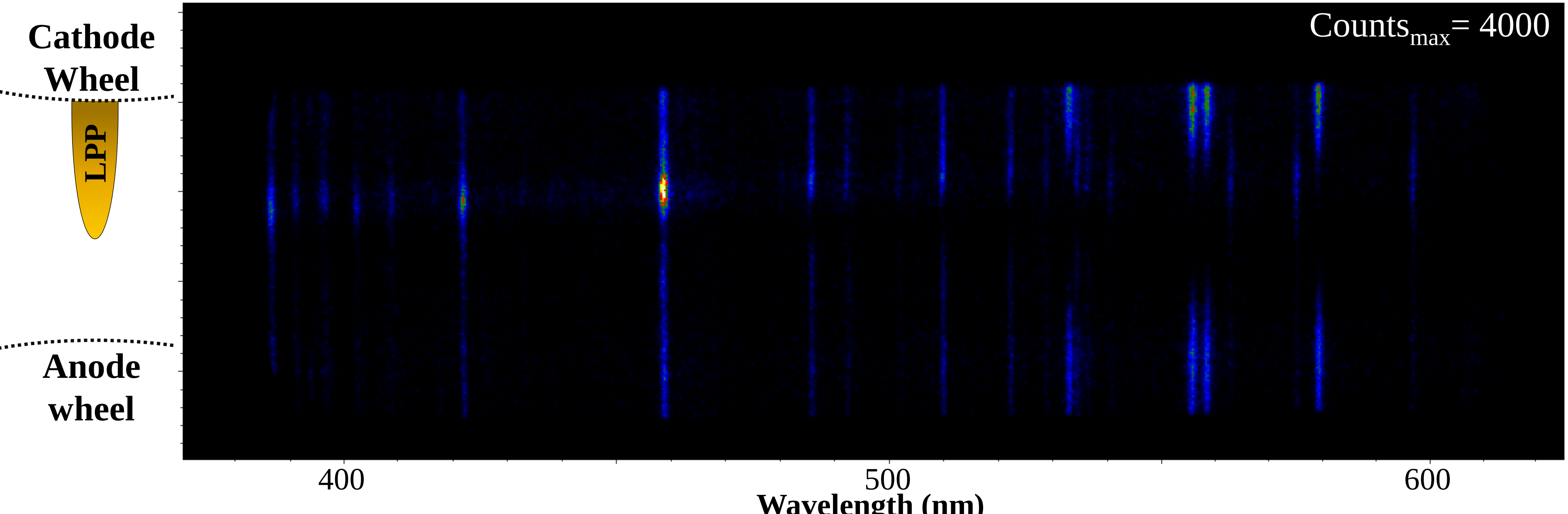

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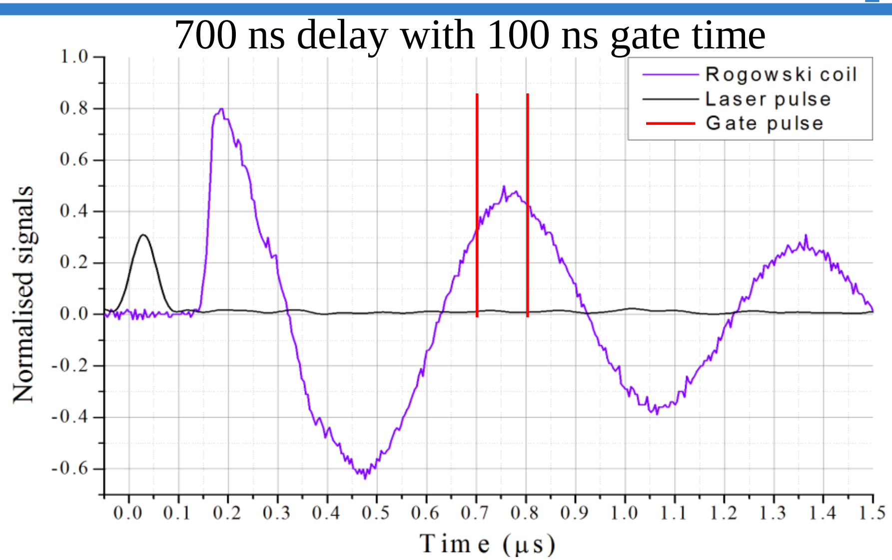

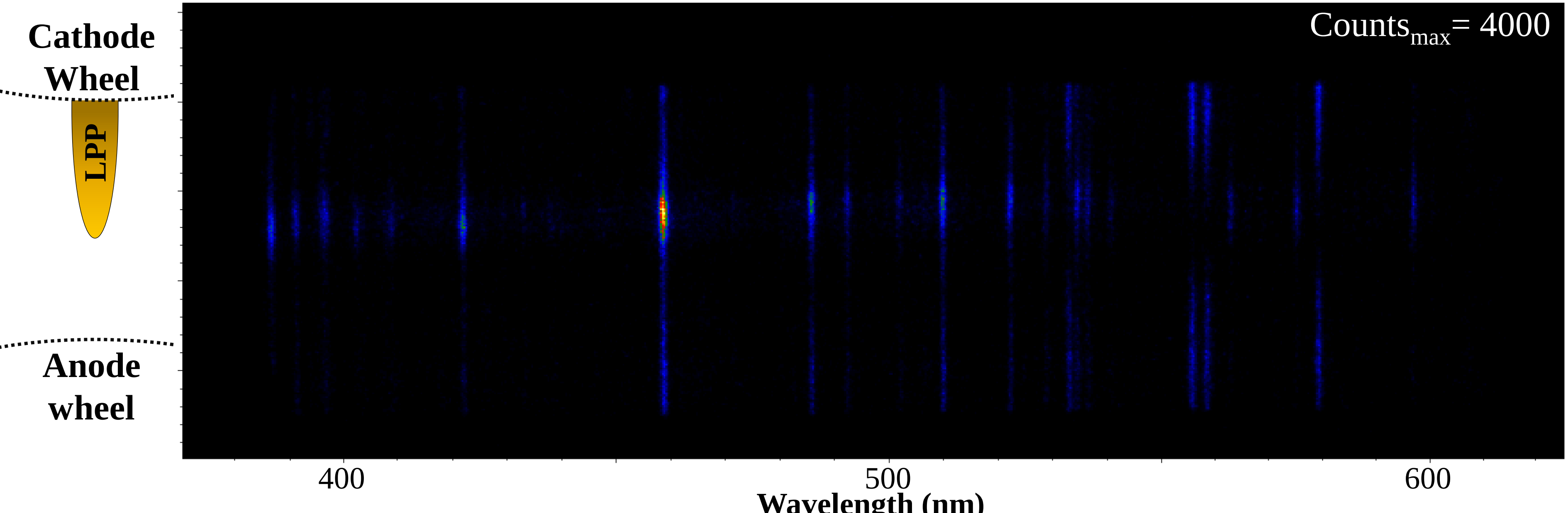

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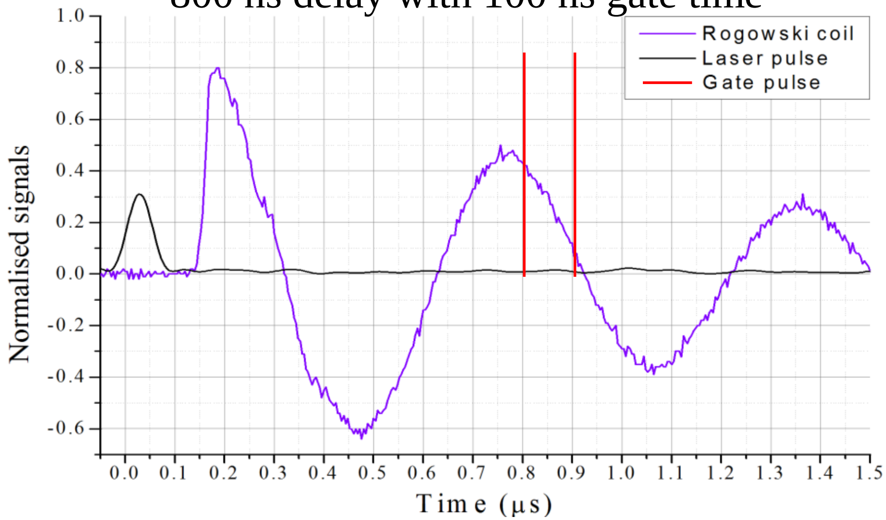
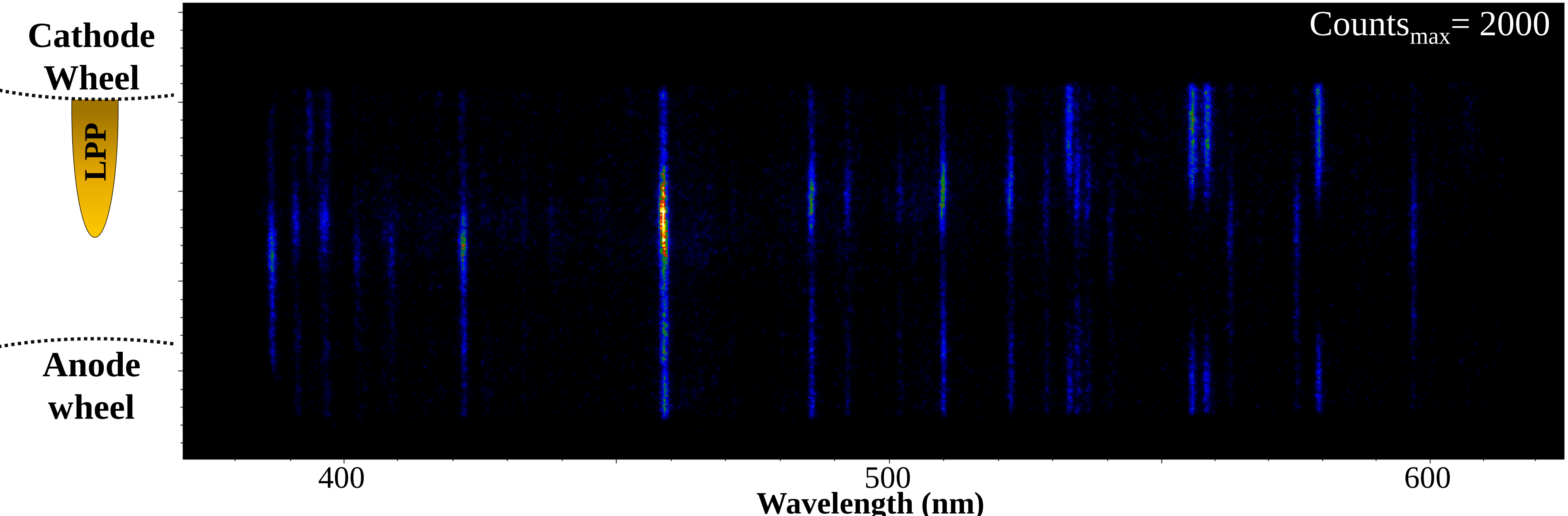
Laser Assisted Vacuum Arc (LAVA) lamp

800 ns delay with 100 ns gate time





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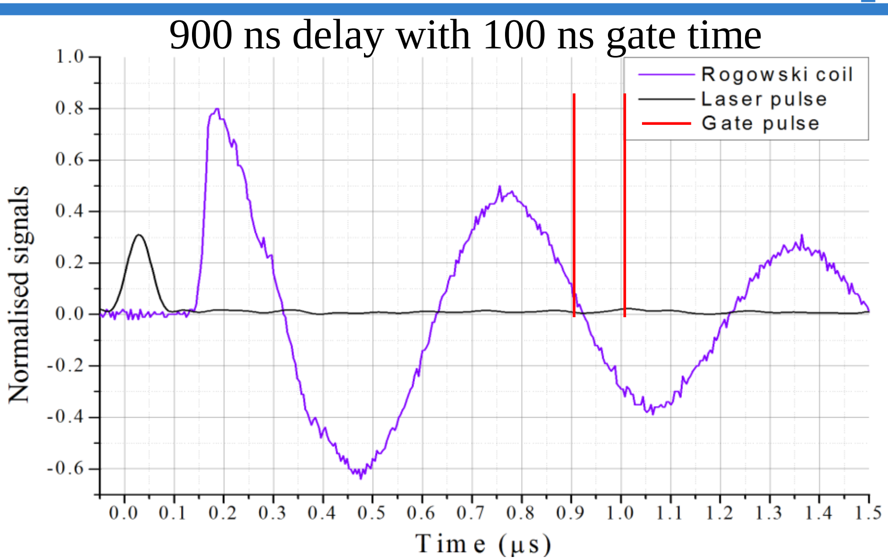
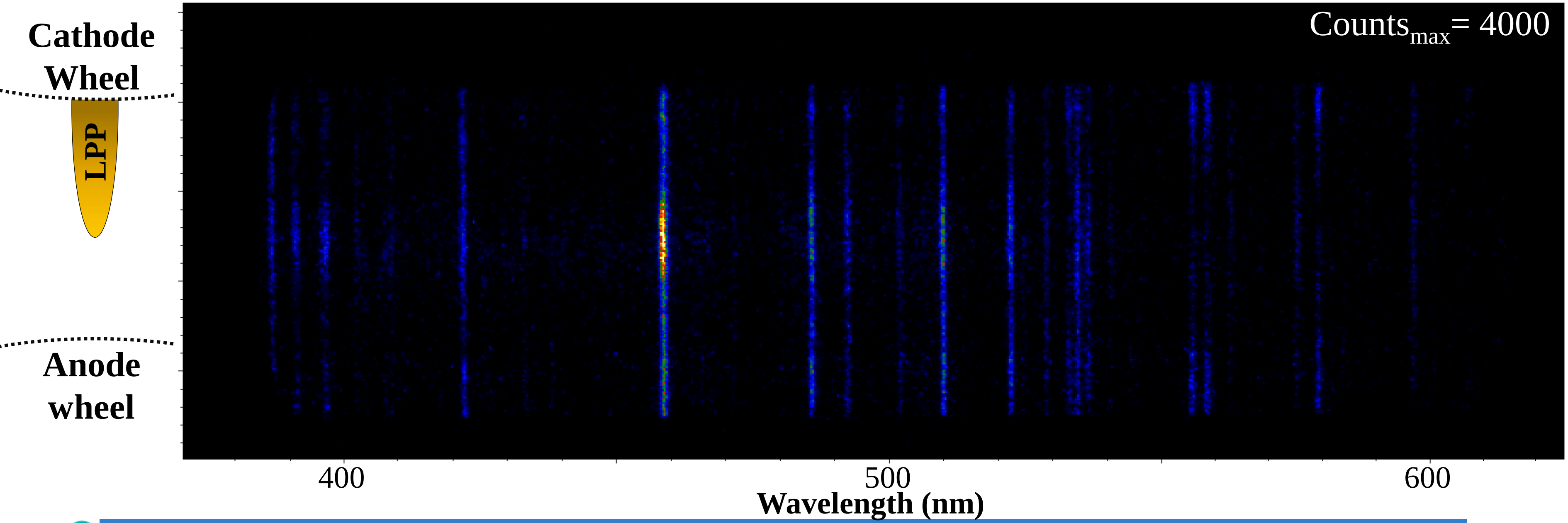
Laser Assisted Vacuum Arc (LAVA) lamp





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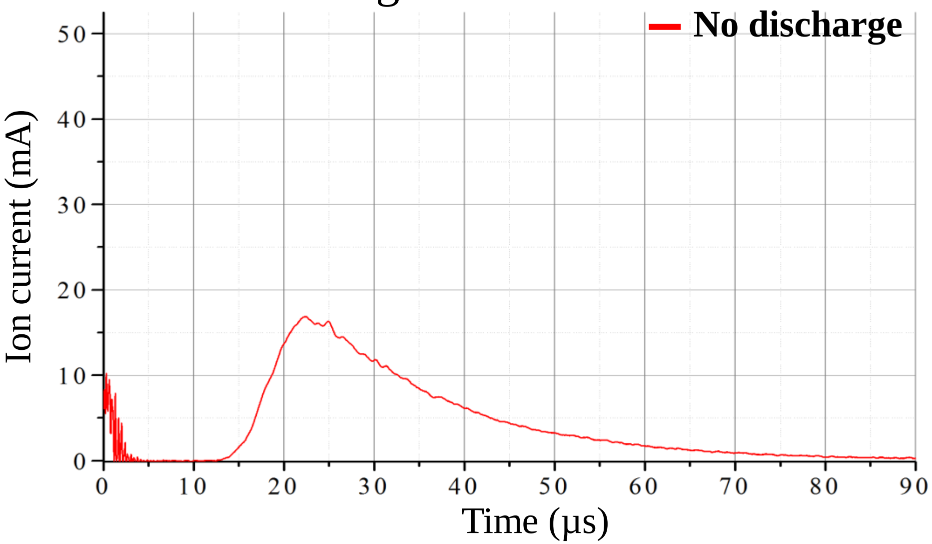
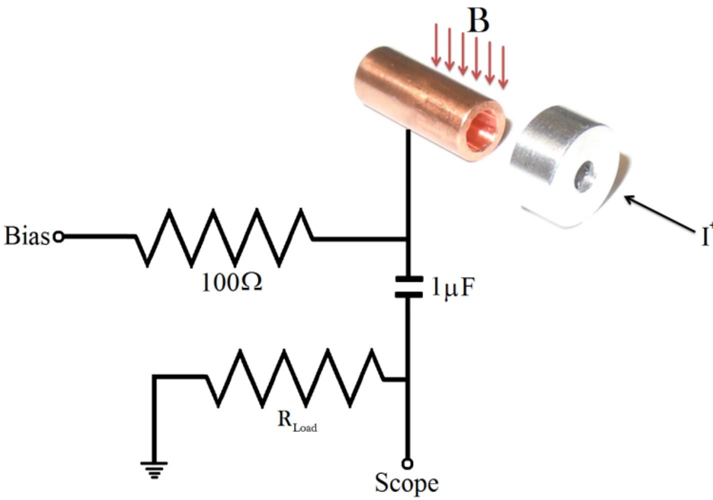
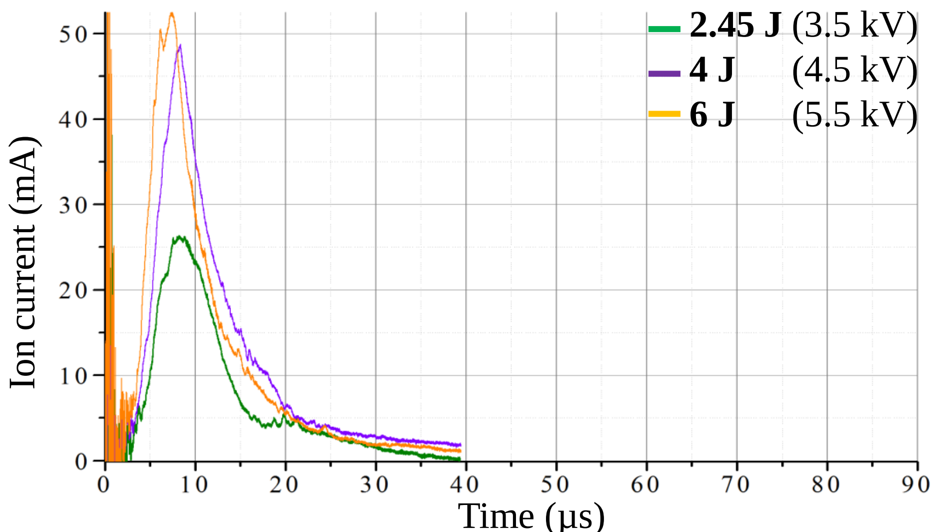
Laser Assisted Vacuum Arc (LAVA) lamp

➤ Sn ion time of flight:





d = 45 cm $\varnothing_{aperture}$ = 2.7 mm
B ~ 65 mT V_{bias} = - 25 V
R_{load} = 296 Ω / 996 Ω



Discharge:	Peak ion velocity:
0 V	0.25 keV
2.45 J (3.5 kV)	1.84 keV
4 J (4.5 kV)	2.03 keV
6 J (5.5 kV)	3.48 keV

Averages of 32 signals for ion currents (E_{laser} 12 mJ)

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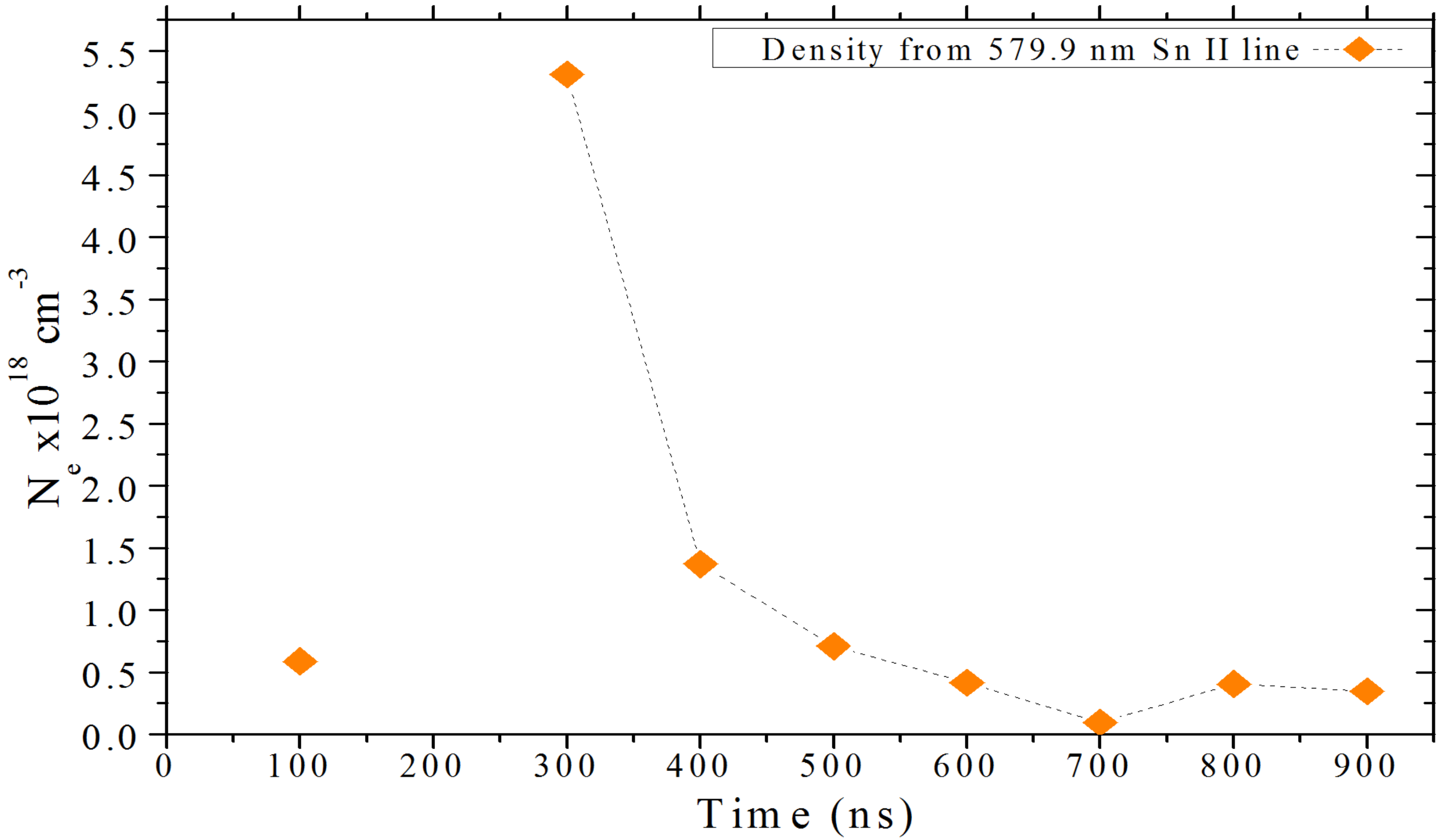
Laser Assisted Vacuum Arc (LAVA) lamp

- Stark broadening analysis:



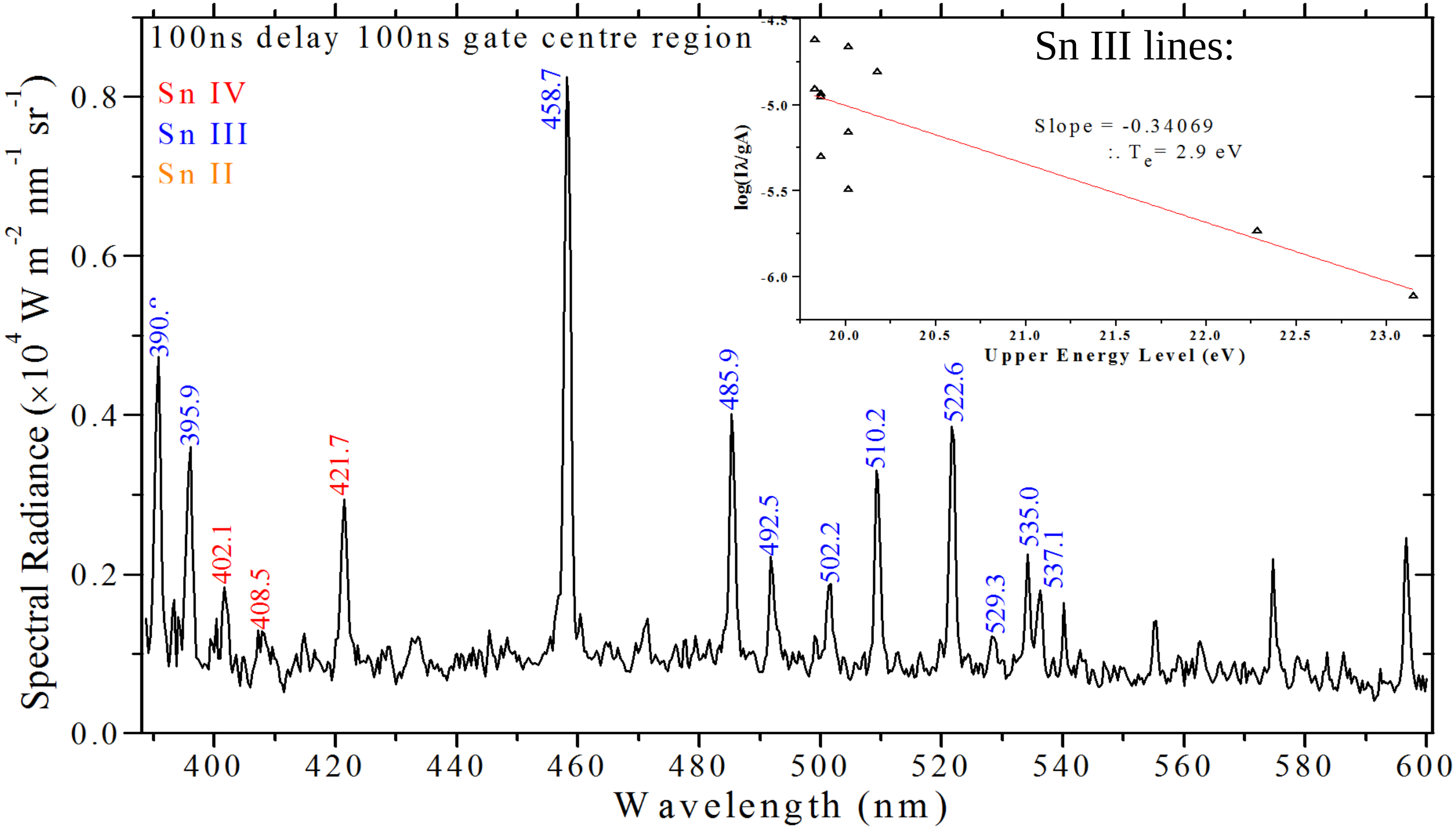
To assume LTE checked McWhirter criterion:

$$Ne \geq 1.6 \times 10^{12} (T)^{\frac{1}{2}} (\Delta E)^3$$

$$\therefore \; Ne \geq 1.9 \times 10^{15} \text{cm}^{-3}$$

Laser Assisted Vacuum Arc (LAVA) lamp

- Boltzmann electron temperature estimates



- Range of electron temperatures estimated for Sn III and Sn IV lines **(~ 2 eV – 6 eV)**
  - → Saha estimate of the **ion temperature in agreement** for this range

- **Not confident** in the Boltzmann data, further work needed. Statistical weight issue?

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Conclusions

- We have recorded **time- and spatially-resolved** visible emission spectra for **<u>Sn</u>** and **<u>galinstan</u>** for discharge voltages of **<u>3 kV – 6 kV</u>** (along with 0 V)

  - **Clear broadening** during the onset of discharge and during pinch phase
    → Densities of up to ~ 5.5×10^{18} cm^{-3} following pinch phase

  - A range of temperatures have been estimated **(~ 2 eV – 6 eV)**
    → Further work needed to increase confidence

  - Finer time steps (**Δt = 20ns**) **to be analysed** to further show evolution of plasma

  - Further **diagnosis of Ga and In lines** needed (any advice/help welcome)

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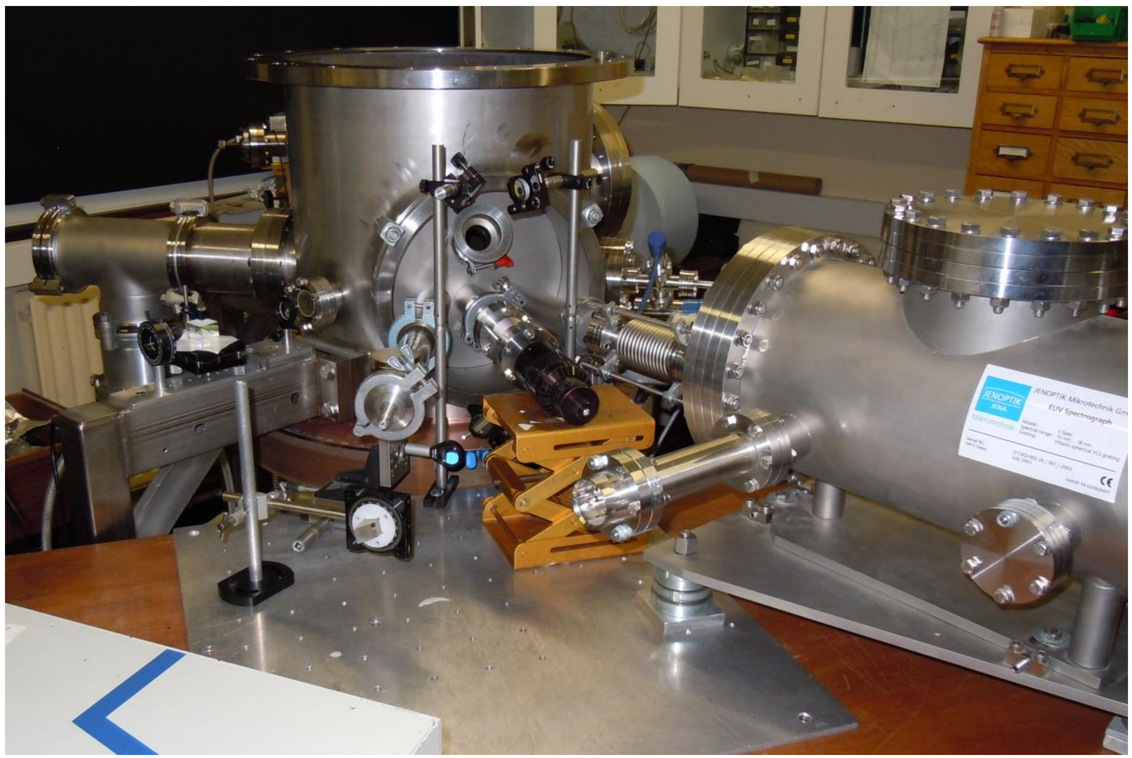
&

And finally,

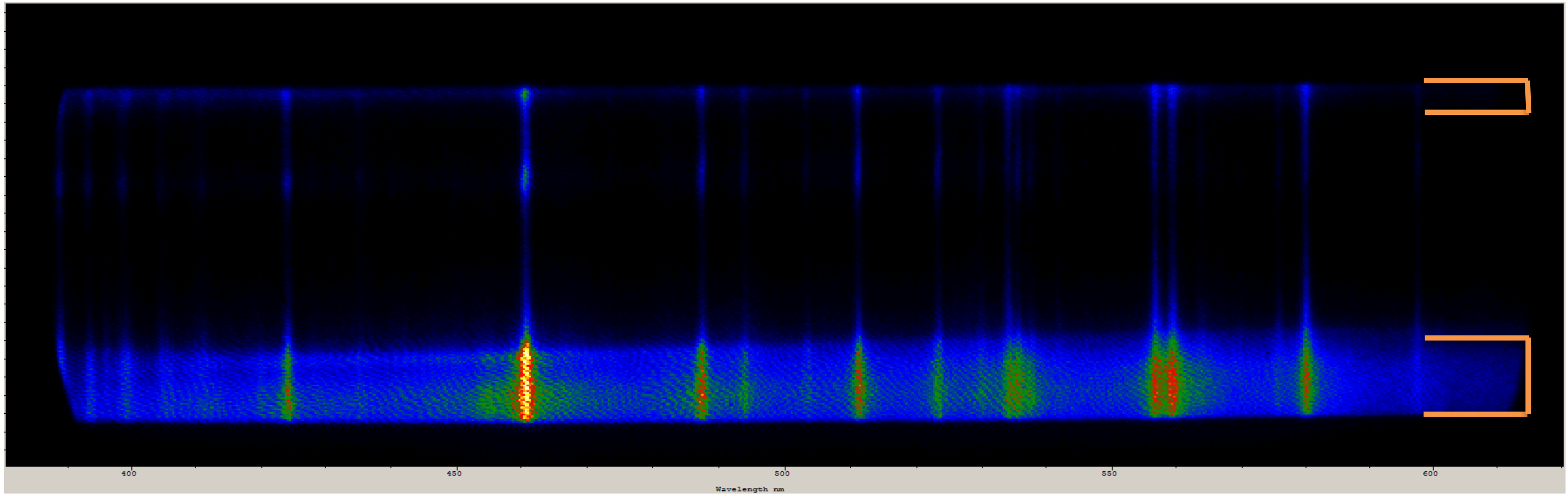
thanks for your attention!



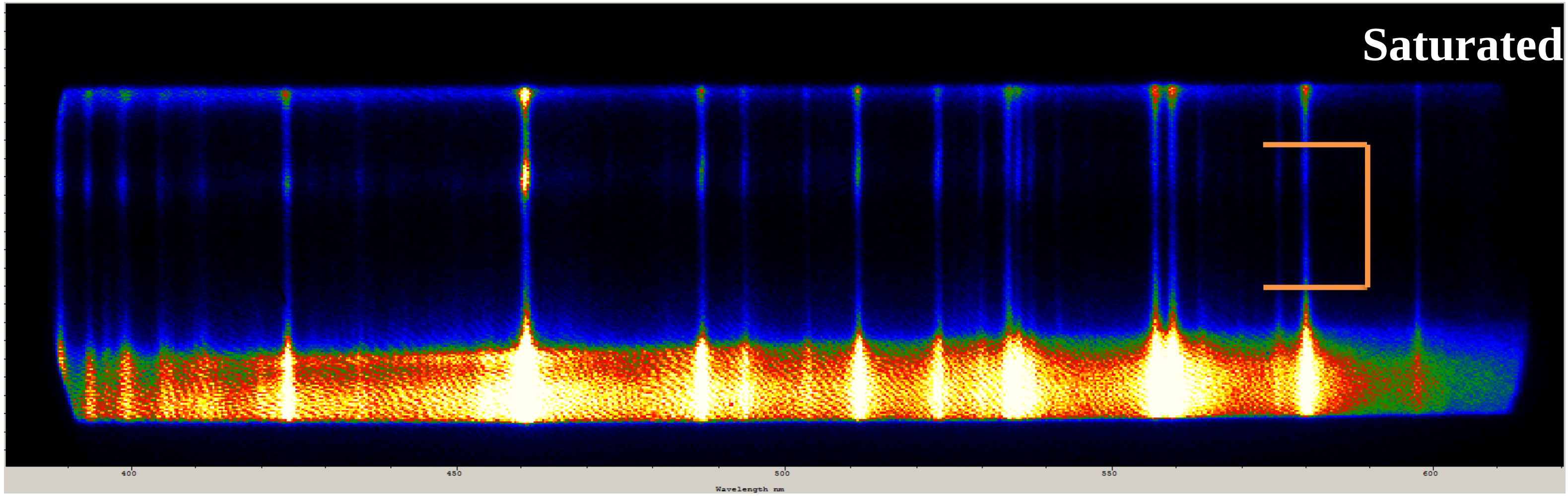
LAVA-lamp, Speclab, UCD

1 μs gate time:

Sn, 4 J (4.5 kV), trigger laser 12 mJ, color scale (min – max): 0 - 15000 counts

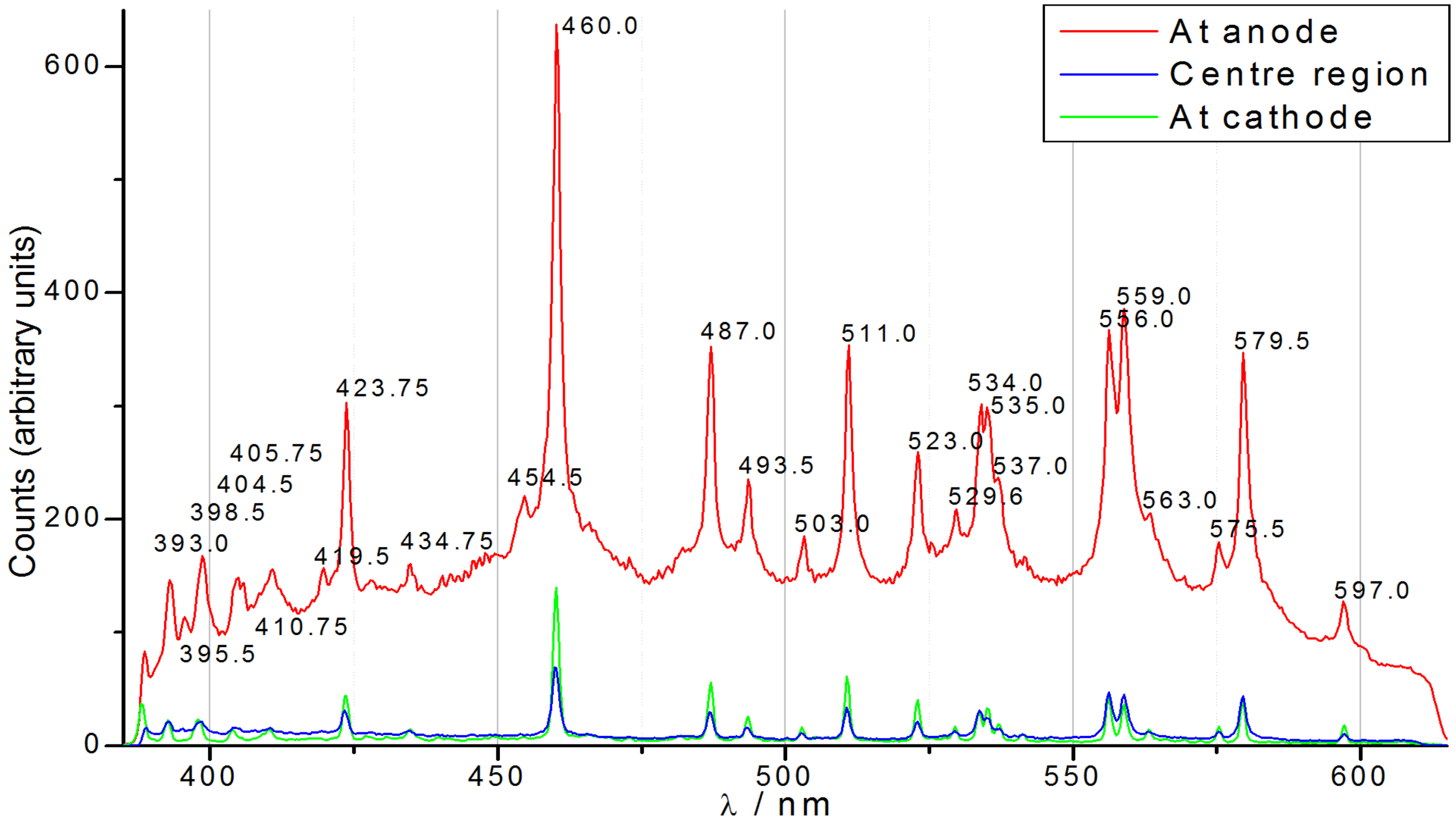


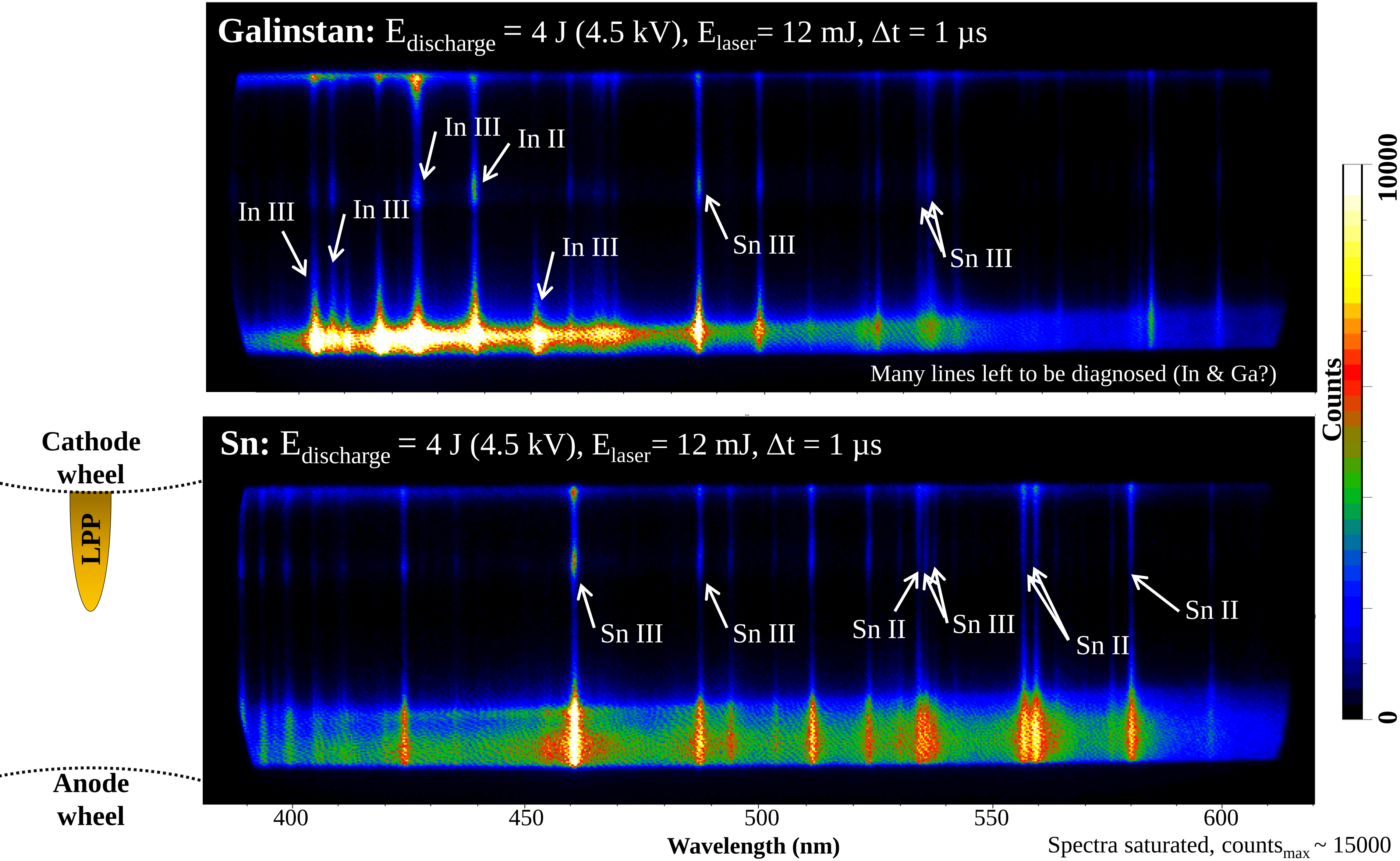
Sn, 4 J (4.5 kV), trigger laser 12 mJ, color scale (min – max): 0 - 5000 counts



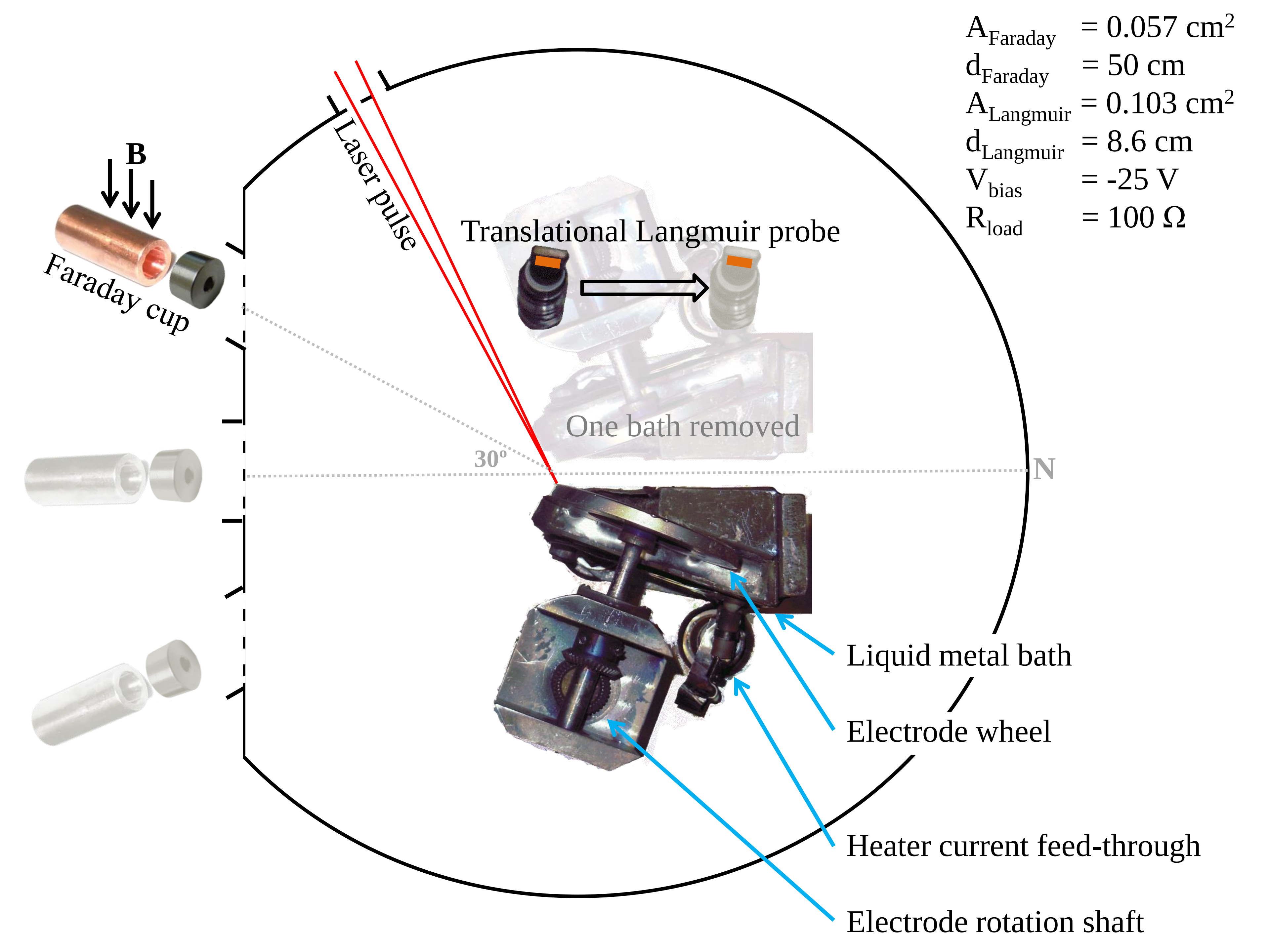
1 μs gate time:

Sn, 4 J (4.5 kV), trigger laser 12 mJ





Galinstan: $E_{discharge}$ = 4 J (4.5 kV), E_{laser}= 12 mJ, Δt = 1 μs
In III
In II
In III
In III
In III
Sn III
Sn III
Many lines left to be diagnosed (In & Ga?)
Sn: $E_{discharge}$ = 4 J (4.5 kV), E_{laser}= 12 mJ, Δt = 1 μs
Cathode wheel
LPP
Anode wheel
Sn III
Sn III
Sn II
Sn III
Sn II
Sn II
400
450
500
550
600
Wavelength (nm)
Spectra saturated, $counts_{max}$ ~ 15000
Counts
10000
0


$A_{Faraday}$ = 0.057 cm^2
$d_{Faraday}$ = 50 cm
$A_{Langmuir}$ = 0.103 cm^2
$d_{Langmuir}$ = 8.6 cm
V_{bias} = -25 V
R_{load} = 100 Ω
B
Faraday cup
Laser pulse
Translational Langmuir probe
One bath removed
30º
N
Liquid metal bath
Electrode wheel
Heater current feed-through
Electrode rotation shaft